Predicting the future of the endemic cactus Melocactus pachyacanthus in a semiarid landscape

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Abstract

Anthropogenic activities have increasingly pressured biodiversity worldwide. The cactus *Melocactus pachyacanthus*, an endemic and endangered species of Brazil´s Caatinga biome, is particularly vulnerable. This study assessed the effects of climate change, land use, and fire on the distribution of *M. pachyacanthus* across three ecoregions in the Chapada Diamantina region, Bahia, Brazil. We employed Ecological Niche Modeling (ENM) to evaluate current climatic suitability and to project future scenarios, overlaying ENM outputs with land-use and fire data. The current model identified a concentration of suitable habitat in the Southern Sertaneja Depression. At the same time, future projections reveal a reduction in this region and an expansion toward the Chapada Diamantina Complex. Although land use significantly contributed to habitat loss, fire had a lesser impact. Our findings underscore the importance of ENM as a tool for identifying priority conservation areas and guiding the creation of Environmental Protection Areas. These results highlight the urgent need for conservation policies to safeguard endemic species like *M. pachyacanthus* amid ongoing environmental changes. Our research provides insights into how climate and human activities reshape species distributions in semi-arid regions worldwide.

1. Introduction

Given the constant changes driven by human activities related to climate change, land use and occupation, and fires in the Caatinga biome, measuring the potential impacts of these anthropogenic activities on local biodiversity has become increasingly necessary (Silva, 2023)[32]. The Caatinga is a seasonally dry tropical forest located in a semi-arid tropical climate marked by high average annual temperatures and long periods of drought (Fernandes, 2018)[14]. Its specific edaphoclimatic characteristics have given it a rich diversity and endemic species (Taiz & Zeiger, 2006)[34]. As one of the world's most biodiverse semi-arid biomes (Tabarelli et al., 2018)[33], the Caatinga hosts a rich flora and fauna adapted to extreme conditions, making the conservation of endemic species essential for ecological resilience (Fernandes & Queiroz, 2018)[14].

Representing the endemic species of the Caatinga, *Melocactus pachyacanthus* Buining & Brederoo is a cactus (Martinelli & Moraes, 2013)[26] with a succulent subshrub habit that is found on flat rocky outcrops (Zappi & Taylor, 2023)[39], where the exposed limestone is exploited (Zappi et al., 2011)[38]. The known uses of this species are ecological, in the foraging of animals typical of the Caatinga, with frugivorous and nectarivorous habits (Cavalcante et al., 2013)[8], mystical-religious, and economic as an ornamental plant (Martinelli & Moraes, 2013)[26]. Slow-growing, this species is quite vulnerable to environmental disturbances, including increases in temperature and loss of habitat quality during its initial stages of development (Cavalcante et al., 2013)[8].

This vulnerability is quite worrying, given that projections of future climate change for the Caatinga biome are pessimistic and that frequent emissions of greenhouse gases (GHGs) are expected. Reductions in precipitation and increases in annual temperature tend to desertify this region (Tavares & Ramos, 2016; Tavares et al., 2019)[36, 35]. Soil exploitation for agricultural purposes is another factor that significantly impacts this biome (Martinelli & Moraes, 2013)[26]. Intensive farming practices are among the main factors responsible for converting areas of native vegetation into monocultures and pasture plantations (Martinelli & Moraes, 2013)[26]. In this context, illegal deforestation for land use and occupation is one of the causes of the increasing expansion of fire (Silva et al., 2023)[32]. In addition, fire outbreaks have been increasing significantly in the Caatinga and may be directly associated with climate change; they can impoverish the nutritional attributes of local soils (Diele-Viegas et al., 2022; Boff, 2018; Macedo, 2023)[9, 4, 23].

Ecological Niche Modeling (ENM) is an approach widely used by ecologists to predict species' distribution and occurrence patterns (Barbet-Massin, 2012)[3]. Using ENM, it is possible to generate maps of species' environmental suitability based on their realized niche and project these models for different environmental scenarios (Barbet-Massin, 2012; Santos et al., 2024)[3, 31]. Identifying this suitability is essential to defining the potential areas of occurrence of the species to be restored and protected.

Thus, to conserve *Melocactus pachyacanthus*, an "Endangered" of extinction (EP) in the wild (Brasil, 2022) [7], we measure the impacts of human activities related to climate change, land use, and fire on its occurrence. The specific objectives were I. to map the potential areas of bioclimatic suitability for the occurrence of the species *M. pachyacanthus* in the current scenario; II. to predict the potential bioclimatic suitability for the occurrence of the species *M. pachyacanthus* considering optimistic future scenarios about GHG emissions, and, III. to assess the impact of land use and occupation and fire on the potential occurrence of *M. pachyacanthus* in the current scenario.

2. Methodology

2.1 Study area

The study area is delineated around the three ecoregions of Chapada Diamantina in Bahia, Brazil: Southern Sertaneja Depression (SSD), Chapada Diamantina Complex (CDC), and São Francisco Dunes (SFD). The selection considered the locations of known occurrence points for *Melocactus pachyacanthus* (Fig. 1).

(Fig. 1 Location of occurrence points *Melocactus pachycanthus* in ecoregions)

The DSM ecoregion covers an area of 373,900 km^2, except the Campo Maior Complex ecoregion, which borders all the ecoregions of Chapada. It encompasses the CDC and the SFD. Its vegetation is more typical of the semiarid to arid Northeast, and the predominant climate is hot and semiarid (Velloso et al., 2002)[37].

The CDC covers an area of 50,610 km^2. Located in the center-south of the Caatinga, it is considered the biome's highest region. The extensive reworking of these areas has created deep valleys. The climate of this ecoregion ranges from hot to tropical in the western part and tropical to semiarid in the eastern part (Velloso et al., 2002)[37].

The SFD area is part of the central-western biome, covering 36,170 km^2. With a scorching, semiarid climate, this ecoregion has high soil temperatures and is characterized by extensive wind farms with caatinga vegetation grouped into thickets (Velloso et al., 2002)[37].

2.2 Geographical space

The species' occurrences were collected from the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/). A total of 33 occurrences were found. The occurrence points were filtered to remove points in the ocean, municipal centroids, and duplicate occurrences. The remaining 16 points were used to perform correlative modeling with bioclimatic variables (Table 1).

Table 1
Spatial data on the occurrence of the species *Melocactus pachycanthus* in the ecoregions and municipalities of Bahia.

ID	Spatial Location of Occurrence points			
	Ecorregiões	**Lat**	**Long**	**Municipality**
1	Southern Sertaneja Depression	-11.01333	-41.676246	São Gabriel
2	Southern Sertaneja Depression	-10.883588	-41.160171	Ourolândia
3	Chapada Diamantina complex	-11.525812	-41.182406	Morro do Chapéu
4	Southern Sertaneja Depression	-9.594404	-40.315713	Juazeiro
5	Southern Sertaneja Depression	-11.305921	-41.838276	Irecê
6	Southern Sertaneja Depression	-11.681666	-41.673889	Canarana
7	Chapada Diamantina complex	-11.089444	-41.085278	Varzéa Nova
8	Southern Sertaneja Depression	-9.977638	-40.884175	Campo Formoso
9	Southern Sertaneja Depression	-11.414721	-41.406111	América Dourada
10	Chapada Diamantina complex	-11.013611	-40.407778	Saúde
11	Chapada Diamantina complex	-11.41361	-40.407778	Miguel Calmon
12	Southern Sertaneja Depression	-11.50000	-41.70000	
13	Southern Sertaneja Depression	-10.046919	-41.126198	Campo Formoso
14	Southern Sertaneja Depression	-11.3000000	-41.420000	América Dourada
15	Southern Sertaneja Depression	-10.153381	-40.732417	Campo Formoso
16	Southern Sertaneja Depression	-10.856956	-41.660072	São Gabriel

2.3 Environmental Space

The 19 bioclimatic variables of WorldClim 2.0 were collected with 2.5’ arc-minutes (~ 5 x 5km) (Fick & Hijmans, 2017)[15]. We cropped the variables to the study area and removed bioclimatic variables 8, 9, 18, and 19. These variables combine precipitation and temperature data and present anomalies as unrealistic spatial discontinuities (Escobar et al., 2014)[13]. To reduce collinearity, we removed correlated variables ($r > 0.7$) using Pearson’s Correlation (Dormann et al., 2013)[11]. The uncorrelated bioclimatic variables selected for the model were BIO3- Isothermality (BIO2/BIO7) (×100), BIO10- Average temperature of the warmest quarter, and BIO12 - Annual precipitation.

2.4 Ecological niche model

We used three algorithms in the modeling process: Bioclim (Rangel & Loyola, 2012)[30], Support Vector Machine (SVM) (Rangel & Loyola, 2012)[30], and Generalized Linear Model (GLM) (McCullagh & Nelder, 2019)[25]. For each algorithm, we ran 10 bootstrap replicates, where 70% of the occurrences were used for training and 30% for testing. During model testing, we generated random pseudo-absences: 10,000 points for the GLM and 160 points (10 times the number of presences) for the Bioclim and SVM models (Barbet-Massin et al., 2012)[3]. The models were evaluated using the Area Under the Curve (AUC/ROC; Fielding & Bell, 1997). This metric ranges from 0 to 1, where values below 0.5 indicate random predictions and values above 0.75 indicate good predictions.

Based on AUC, we selected the best replicates for each algorithm and combined them into an ensemble model using an average weighted by AUC 0,75 (Diniz-Filho et al., 2010)[10].

2.5 Model projection and overlay

We project the consensus model for the years 2041–2060 (hereafter referred to as 2050) using the shared socioeconomic pathways (SSP) scenario SSP2 45 and SSPS5 85 (IPCC, 2021)[18]. The SSP2 45 scenario predicts intermediate greenhouse gas emissions that stabilize in 2050, resulting in a 2.0°C increase, while the SSP5 85 scenario predicts very high greenhouse gas emissions that triple from 2075 onwards, with a 2.4°C increase in 2050 (IPCC, 2021)[18]. Future climate projections were performed with the ensemble (average) of three global circulation models (GCMs) from the Coupled Model Intercomparison Project Phase Six (CMIP6) (Eyring et al., 2016)[12]. We selected the best performing GCMS in South America (Oliveira et al., 2023)[27]: (1) Beijing Climate Center model (BCC-CSM2-MR); (2) Institute Pierre Simon Laplace model (IPSL-CM6A-LR); and (3) Model for Interdisciplinary Research on Climate (MIROC6).

Using the model generated to date, we estimated the suitability threshold that maximizes the True Skill Statistic (TSS; Andrade et al., 2020)[1] validation metric. The threshold was used to transform the present models and the projections for the future into binary maps (presence/absence). To understand the impact of land use and fires on the species' habitat, we separately overlapped the binarized models on the land use and fire maps. Thematic maps from collection 8 of the MapBiomas project (Time series 1985–2024), (Jr-Souza et al., 2020)[20] and fire maps (MapBiomas, https://plataforma.brasil.mapbiomas.org/monitor-do-fogo) were used to overlay the present models.

3. Results

3.1 Mapping the bioclimatic suitability of the species *Melocactus pachyacanthus* for the current scenario

In the current scenario, the MNE for the species *M. pachyacanthus* predicted a bioclimatic suitability area of approximately 16.278,90 km^2 across the three ecoregions of interest. In the SSD ecoregion, the area was approximately 41.300,93 km^2, followed by the CDC with 16.278,90 km^2 and the SFD region with 54.136,20 km^2 (Table 2).

Table 2
Calculation of areas of climatic suitability without interference from the variables fire and land use and occupation, and calculation of suitability with interference from the variables fire and land use and occupation, considering the years 1995, 2005, 2015, and 2022 for each variable. CCD - Chapada Diamantina Complex (CCD); DSF - São Francisco Dunes (DSF), and DSM - Southern Sertaneja Depression.

Type map		**Ecorregions**		
	year	**CCD**	**DSF**	**DSM**
Sdm		16278.90278	54.136204	41300.93056
Fire	1995	16278.90278	54.136204	41300.93056
Fire	2005	16278.90278	54.136204	41300.93056
Fire	2015	16173.88851	54.136204	41279.86483
Fire	2022	16154.33523	54.136204	41278.30835
Land use	1995	13130.16218	54.136204	26579.2041
Land use	2005	13370.66189	54.136204	26239.04563
Land use	2015	12375.45984	54.136204	23976.94566
Land use	2022	12554.6199	54.136204	24902.58022

This model showed an increase in suitability variation from 0.6 to 0.8. In the SSD ecoregion, where 81.25% of the species' known occurrence points are located, a larger area of bioclimatic suitability was observed, with a value close to 0.8. In the CDC ecoregion, where 18.75% of the species' known occurrence points are located, suitability was closer to 0.6, a value higher than the DSF. In this ecoregion, where there are no records of the species' occurrence, suitability was below 0.6.

3.2 Prediction of the bioclimatic suitability of the species Melocactus pachyacanthus for the most and least optimistic future climate change scenarios

In climate projections for the most optimistic future scenario, the model predicted suitability for greenhouse gas (GHG) emissions ranging from 0.6 to 0.8. In the SSD ecoregion, the suitability percentage ranged from 0.7 to 0.75. In the CDC ecoregion, where the suitability area expanded, the observed value was close to 0.6, higher than SFD, which was below 0.6 (Fig. 2). In the current scenario, a reduction in the suitability area was observed, with values close to 0.8 in SSD.

Climate projections for the less optimistic future scenario of greenhouse gas emissions also predicted a range of 0.6 to 0.8 in suitability. In the DSM ecoregion, suitability ranged from 0.6 to 0.8. In the CDC ecoregion, suitability was closer to 0.6; in SFD, it was below 0.5 (Fig. 2). On this map, there was an even greater reduction in suitability, with values near 0.8 in DSF. However, an expansion of areas of suitability with percentages close to 0.7 was observed in CDC.

(Fig. 2 Climate projections for future scenarios)

3.3 Interference of land use and occupation on the occurrence of the species Melocactus pachyacanthus in the present bioclimatic scenario

The land-use and occupation maps indicated overlapping areas with altered vegetation cover and possible bioclimatic suitability for *Melocactus pachyacanthus* (Fig. 3). These altered areas also overlapped with the niche occupied by some populations. For the SSD ecoregion, the percentage of overlapping decreased areas in bioclimatic suitability in 1995 was approximately 35.65%.

(Fig. 3 Land-use and occupation maps)

Following this, the land use maps for the years (2005, 2015, and 2022) showed an overlap of approximately 36.47%, 41.95%, and 39.70%, respectively, with the area of bioclimatic suitability predicted in the present model.

At the CDC, the overlap between anthropized areas mapped in 1995 and bioclimatic suitability areas was approximately 19.34%. In 2005, the overlap was approximately 17.87%. In 2015, it was approximately 23.97%; in 2022, approximately 22.88%.

The map did not predict overlap between anthropized areas and bioclimatic suitability for the SFD ecoregion.

3.4 Fire interference in the occurrence of *Melocactus pachyacanthus* in the present bioclimatic scenario

In the SSD ecoregion, the fire maps for 1995 and 2005 did not identify any overlap between fires and potential areas of the species' bioclimatic suitability. However, for 2015 and 2022, the overlap percentages were 0.051% and 0.054%, respectively (Fig. 4).

(Fig. 4 Fire maps)

Regarding the CDC ecoregion, the fire maps did not identify any fire outbreaks in the species' potential areas of occurrence during 1995–2005. For 2015 and 2022, overlaps of 0.64% and 0.77% in fire outbreaks were identified within the potential bioclimatic suitability areas (Fig. 3).

The DSF results for fire, which overlap with areas of present bioclimatic suitability, for the periods 1995, 2005, 2015, and 2022, were negative. The fire map showed no overlap of the burned areas with the occurrence points of the species under study (Fig. 3).

4. Discussions

The need for more favorable temperatures in *Melocactus Pachyacanthus* is related to the species' low tolerance to disturbance in the early stages of its development and its slow growth (Cavalcante et al., 2013)[8]. The ecoregion with the greatest potential for bioclimatic suitability for the species' occurrence was the SSD. The species' chances of survival are possibly greater in this location (Zappi et al., 2011)[38].

This map also showed that some populations occur in areas with lower bioclimatic suitability in the current scenario. It is possible that the climate experienced by the species in the CDC ecoregion is being influenced by its local microclimate (Kearney et al., 2014) [21]. In this region, soil and climate conditions are somewhat different from those in the other regions due to the formation of islands through isolation processes (Velloso et al., 2002)[37].

For the SSD ecoregion, the intensification of climate change (Cavalcante et al., 2013)[8] is reflected in the reduction of the bioclimatic suitability predicted for this location in future scenarios (Pritchard & Harrot, 2010)[29]. With this loss of habitat quality, maintaining *Melocactus pachyacanthus* in these locations would require adaptation to this new scenario (Pritchard & Harrot, 2010) [29]. However, this is unlikely given the short time over which climate change has occurred (Pritchard & Harrot, 2010)[29]. In this bioclimatic context, migration or dispersal could be an alternative to prevent species extinction.

Evaluating the influence of land use and occupation is essential to consider migration as a survival measure, as it strongly shapes species' conservation processes (Pritchard & Harrop, 2010)[29]. Currently, agricultural practices are among the leading causes of habitat destruction and fragmentation for this species (Tabarelli et al., 2018)[33], making it less viable for populations to colonize new areas (Pritchard & Harrop, 2010)[29]. The land-use and occupation map shows the growth of degraded regions over the years (1995, 2005, 2012, and 2022). This growth was observed in the species' fundamental niche and in the areas where the species occurs. Although they still occur in these degraded areas, the species' populations are declining (Martinelli & Moraes, 2013)[26].

Fire has also been increasingly present in the Caatinga Biome (Silva et al., 2023; Jesus et al., 2020)[19, 32]. The maps showing the impacts of fire showed an increase in fire outbreaks in areas of climatic suitability predicted for the current scenario. Still, the percentage values indicating the presence of these outbreaks are insignificant. Despite this, fire may pose an imminent risk to the species due to uncontrolled burning practices that spread fire to surrounding areas, damaging soil quality and vegetation (Baker et al., 2013; Luz et al., 2023)[2, 22].

Based on these results, it is possible to begin considering measures to minimize the impacts of anthropogenic activities on the occurrence of *Melocactus pachyacanthus* (Zappi et al., 2011)[38]. One of them would be the creation of recovery plans for degraded areas in potential bioclimatic suitability areas. Since bioclimatic suitability is expected to decline in future scenarios, restoring degraded, climatically suitable areas would be one possible path.

In conjunction with this action, creating Protected Areas (PAs) of Integral Protection (IP) that guarantee the protection of these areas is fundamental to this process, primarily because PAs are legally protected areas established by law to preserve biodiversity (Boff, 2018; Brasil, 2000) [4, 6]. The prediction of the potential regions of environmental suitability also contributes positively to a more effective management plan for the conservation of the species *M. pachyacanthus* (Rangel & Loyola, 2012)[30] by mapping the areas that have the most favorable environmental conditions for the survival of this species (Paglia et al., 2012)[28]. It is also essential that the management plan for this PA addresses these needs in its preparation (Rangel & Loyola, 2012)[30], so that these areas receive the appropriate categorization of their uses (Brasil, 2000)[6].

In conclusion, the persistence of *Melocactus pachyacanthus* is closely tied to the interplay between its ecological constraints and rapidly changing environmental conditions. Although the SSD ecoregion currently represents the most favorable area for the species, future climate scenarios indicate a decline in suitability, while populations already occurring in less suitable regions may depend on localized microclimatic conditions for survival. Limited dispersal capacity, combined with increasing habitat degradation driven by agricultural expansion and, to a lesser extent, fire, further restricts the species’ ability to track suitable environments. Given these constraints, conservation efforts should prioritize restoring degraded yet climatically suitable areas and establishing well-managed protected areas to safeguard remaining populations. Integrating bioclimatic predictions with land-use planning will be essential to enhance the effectiveness of conservation strategies and mitigate the impacts of ongoing environmental change on this vulnerable species.

Declarations

Ethics, Consent to Participate, and Consent to Publish

Not applicable.

Competing interests

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Author Contribution

Flávia dos Santos Bomfim: Methodology, Research, Formal analysis, Data curation, Writing original draft, Writing final document. Luisa Maria Diele-Viegas: Methodology, Research, Formal analysis, Data curation, Conceptualization, Writing original draft, Writing final document, Review & editing. Thieres Santos Almeida: Methodology, Formal analysis, Data curation, Writing original draft, Review & editing. Bianca Barros Zaballa: Research, Methodology, Data curation, Writing original draft. Mateus Almeida dos Santos: Methodology, Data curation, Writing original draft, Review & editing. Hugo Andrade: Data curation, Writing original draft, Review & editing. Fernanda Melo Gomes: Methodology, Research, Conceptualization, Writing original draft.

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Data Availability

ll data supporting the findings of this study are available within the paper.

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Figures

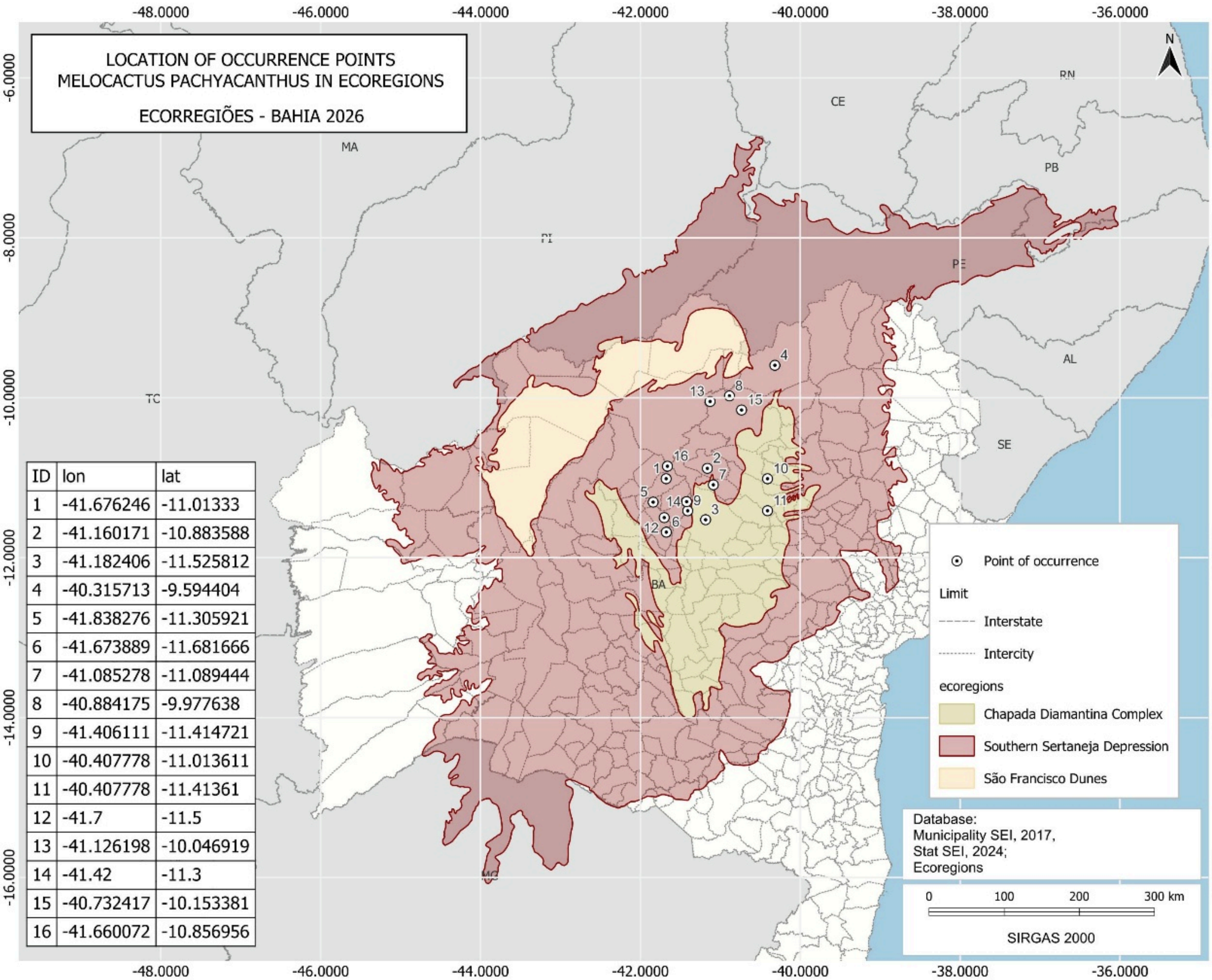

Figure 1

Location of occurrence points *Melocactus pachycanthus* in ecoregions

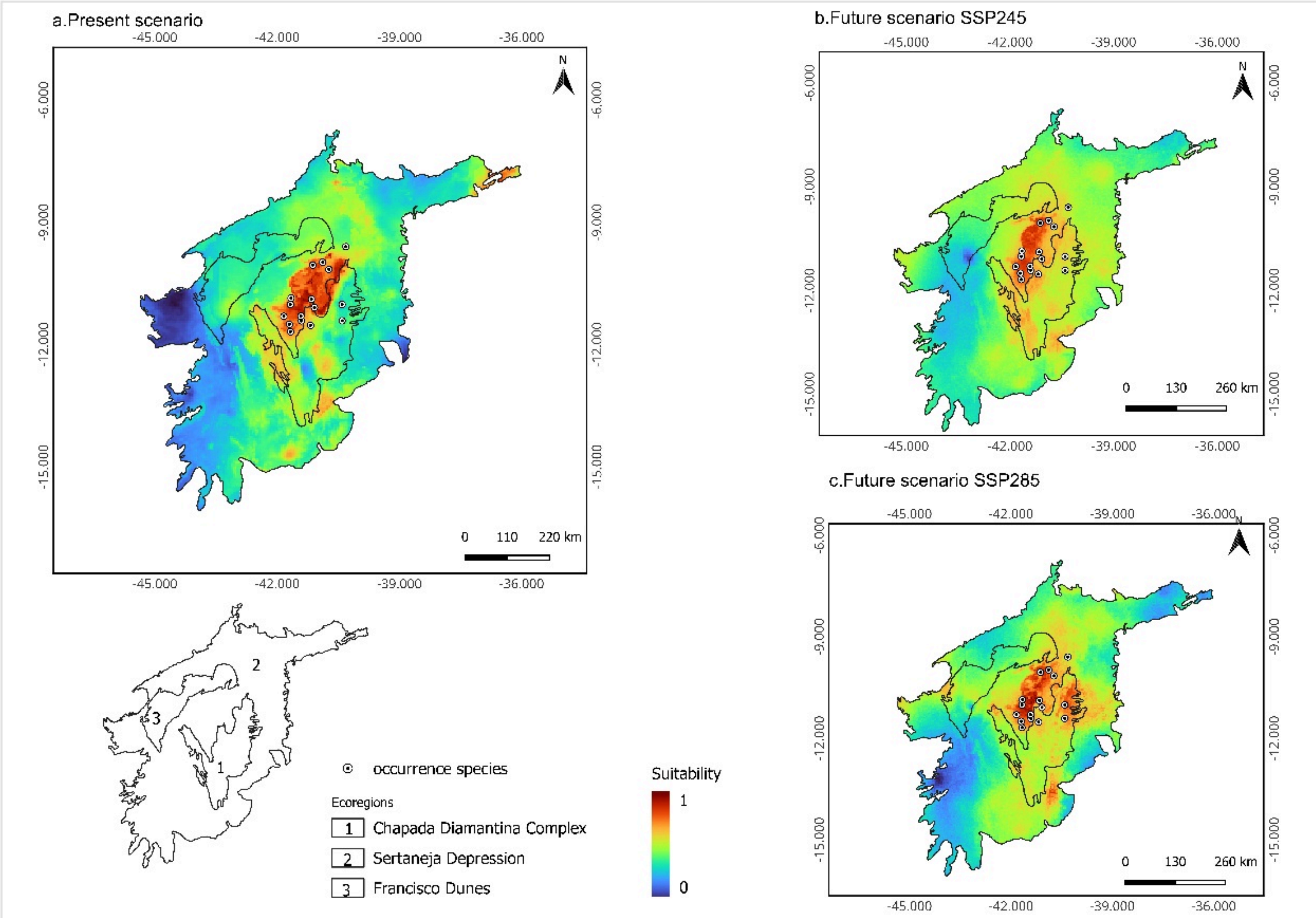

Figure 2

Climate projections for future scenarios

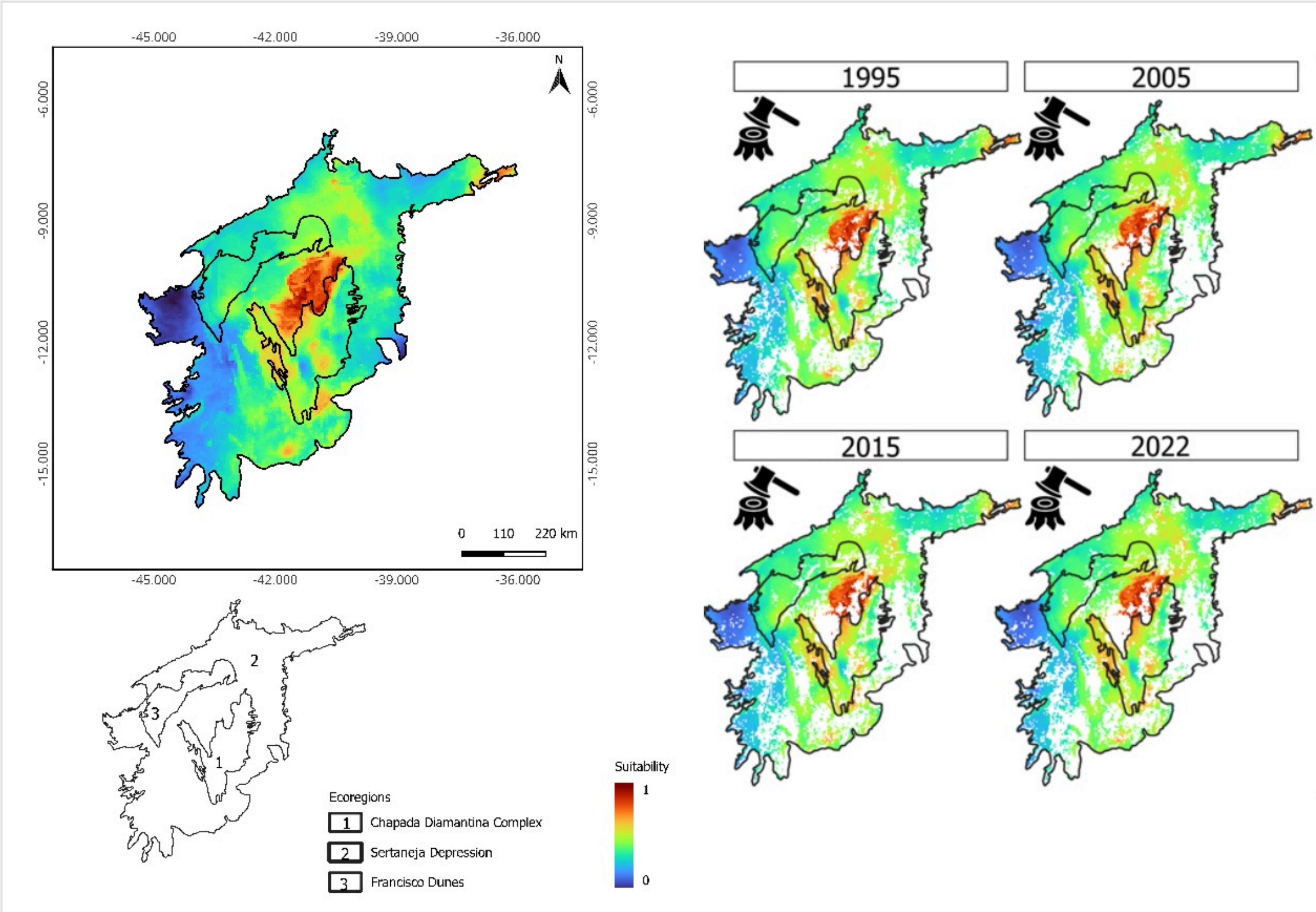

Figure 3

Land-use and occupation maps

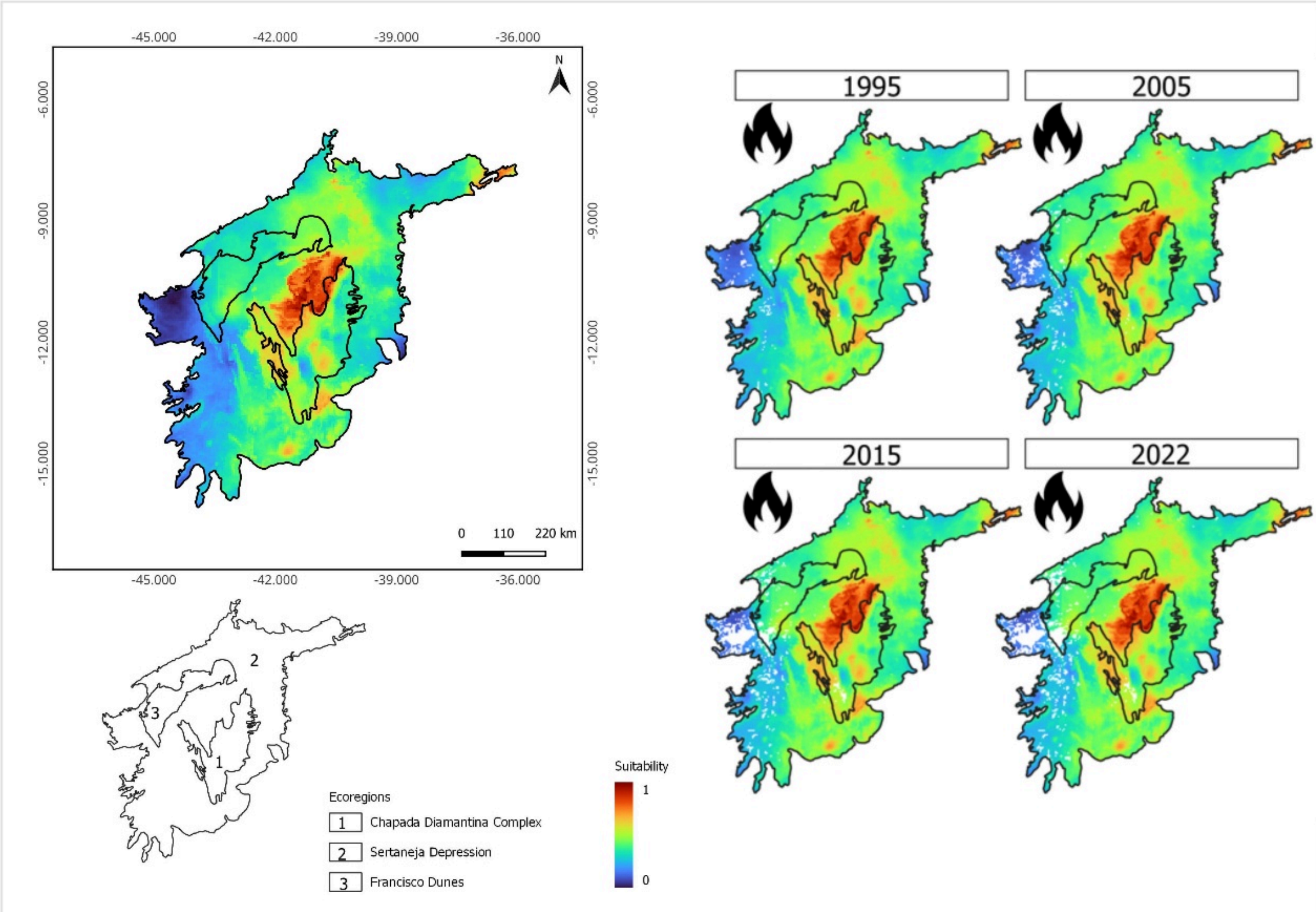

Figure 4

Fire maps